Cover sheet

Human factors of 3-D perspective displays for command and control

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Abstract

Effective Command and Control (C2) requires the rapid comprehension of the identity and other attributes of tracks and other objects in three-dimensional (3-D) space. Advances in computing speed and power are enabling display designers to create real-time prototype 3-D displays for this purpose. By 3-D display, we mean a display that shows a perspective projection of all three dimensions of physical space onto a flat CRT. One example of a 3-D prototype C2 display is the Area Air Defense Commander (AADC) prototype display (Dennehy, Nesbitt & Sumey, 1994). These new 3-D prototypes are extremely compelling. They offer a radical increase in realism of the scenes they depict over existing 2-D C2 displays. Their naturalistic look and easy feel make them attractive to users who consistently express a strong preference for them. But just because users are clamoring for these 3-D displays and because we can now give them to them does this mean that we **should** advocate their ubiquitous adoption for C2? The experimental literature comparing 2-D and 3-D displays is large, complicated and contradictory, often showing mixed advantages for 3-D displays, at best. The Navy's Perspective Display Technology (PVT) project has been conducting human factors research addressing these issues. In this talk, an array of PVT's experimental studies is reviewed that offer a consistent - and often counter-intuitive - set of results and guidelines to the where, what and how of 3-D perspective display use for C2 tasks.

Introduction

The ongoing revolution in the availability of inexpensive and fast 3-D rendering technologies is allowing display designers to develop 3-D prototype displays C2, such as the one shown in Figure 1 (Dennehy, Nesbitt & Sumey, 1994). By 3-D display, we mean

a display that shows a perspective view of a scene on a CRT or other flat computer display. The image is two dimensional (2-D), but the oblique viewing angle means that all three dimensions are projected and represented, to provide a 3-D perspective. There are various other ‘true’ holographic and stereoscopic 3-D displays under development (e.g., Soltan et al., 1998) but most interest in 3-D displays is in flat screen displays like that shown in Figure 1.

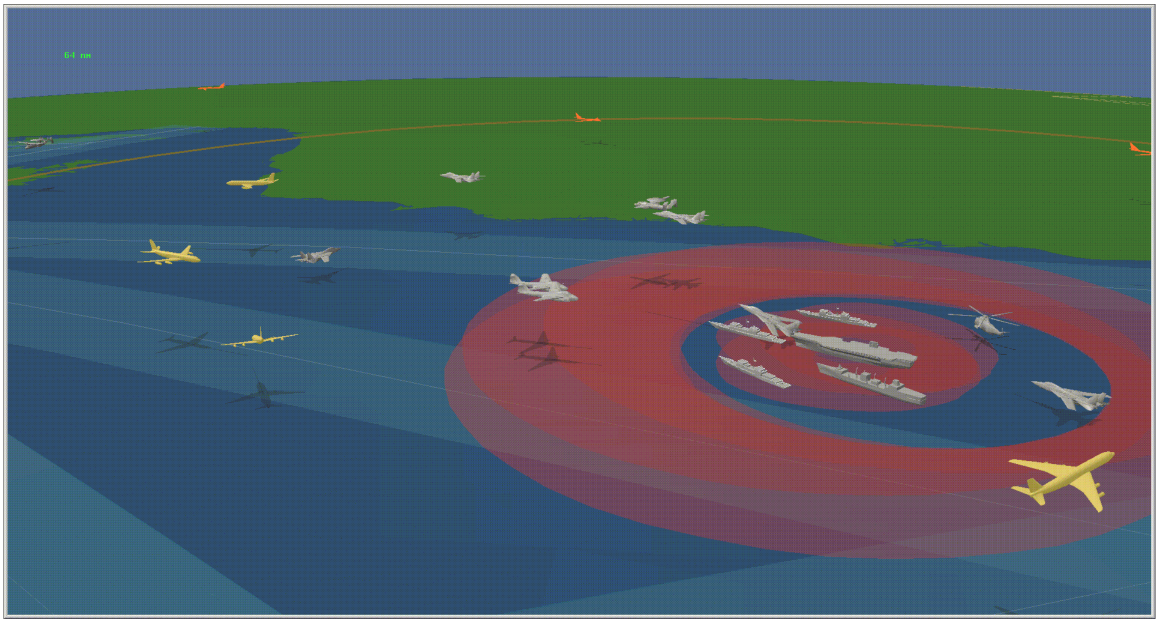

Figure 1. Screenshot from a prototype 3-D perspective display for naval air warfare (from Dennehy, Nesbitt & Sumey, 1994).

There are several reasons to suppose that 3-D displays may be preferable to conventional 2-D displays that show an environment from directly above. First, because our retinal images are perspective projections of the world, 3-D displays may be inherently more ecologically plausible than 2-D displays. Similarly, their naturalistic look has led some 3-D display designers to suggest that they may require “minimal interpretive effort” (Dennehy, Nesbitt & Sumey, 1994). Second, because 3-D displays integrate all three dimensions of space into a single display, users may be spared the mentally demanding process of scanning back and forth to integrate two planar views in order to gauge 3-D spatial relationships (Haskell & Wickens, 1993). Third, users simply prefer the familiarity and easy feel of 3-D displays.

However, there are counter-arguments to each of these points. First, if a scene were reproduced with the exact same fidelity as retinal images of that scene, those images would still need to be interpreted. A century of perceptual work since Helmholtz has documented the difficulties inherent in natural scene interpretation. Second, the compression of three dimensions onto a flat display integrates all dimensions but leaves each one somewhat ambiguous (see Figure 2). This ambiguity, coupled with the distortion of distances and angles inherent in a perspective projection (Sedgewick, 1986),

makes 3-D displays of questionable utility for precise relative position tasks. Third, basing display decisions on user preference is not always sound because users do not always want what is best for them (Andre & Wickens, 1995).

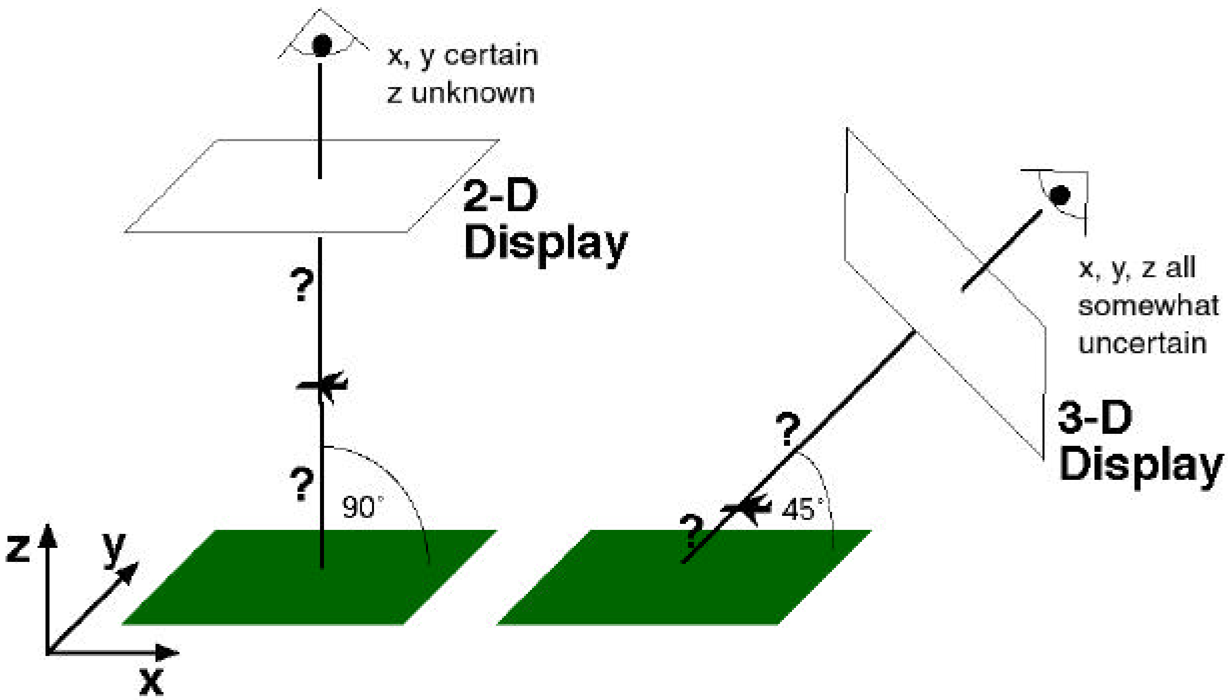

Figure 2. Viewing geometry and line of sight (LoS) ambiguities of 2-D and 3-D displays (from Smallman, Schiller & Cowen, 2000). Position and distance are ambiguous along the line of sight in either viewing geometry.

These conflicting arguments are complimented by a large and ever growing literature documenting a mixed pattern of results for 2-D vs. 3-D display comparisons (for a recent review and synthesis, see St. John, Cowen, Smallman & Oonk, 2001). The Navy's Perspective Display Technology (PVT) project has been conducting human factors research addressing these issues. Here, an array of PVT's experimental studies is reviewed that offer a consistent - and often counter-intuitive - set of results and guidelines to the where, what and how of 3-D perspective display use for C2 tasks.

Where

Static 2-D and 3-D displays differ primarily in their viewpoint location (Figure 2). 2-D displays show the world from a viewpoint directly above, looking down at 90 degrees to the ground-plane. 3-D displays show the world from above and to the side, generally between 25 and 45 degrees to the ground-plane. This difference turns out to greatly affect the ability of the display to depict **where** objects are in space. Unlike 2-D displays, where only the z axis (aircraft altitude) is completely ambiguous, the oblique viewpoint of 3-D displays makes all three dimensions somewhat uncertain. This uncertainty,

coupled with the distortions of distances and angles from perspective projection, throws into question a user's ability to spatially localize objects correctly in 3-D displays.

Given these comparative advantages and limitations, the question is when and how to use 2-D and 3-D displays effectively. We proposed a distinction between tasks that require shape understanding and tasks that require precise judgments of relative position (St. John et al., 2001). We hypothesized that 3-D views are useful for understanding object shape, but 2-D views are more useful for understanding the relative positions of objects. We confirmed these hypotheses in two experiments involving simple block shapes. We created simple 3-D block shapes that were rendered as a 3-D perspective view or as a set of 2-D views (see Figure 3). Participants viewed blocks in 2-D or a 3-D perspective view and either performed a shape understanding task (e.g. identification or mental rotation) or a relative position task (e.g. determining directions and distances between objects or navigation between them). We found that participants were faster and more accurate using the 3-D views for the shape understanding tasks than the 2-D views, even when blocks were rotated 90-degrees. Conversely, with the same stimuli, participants were faster and more accurate using the 2-D views for the relative position tasks.

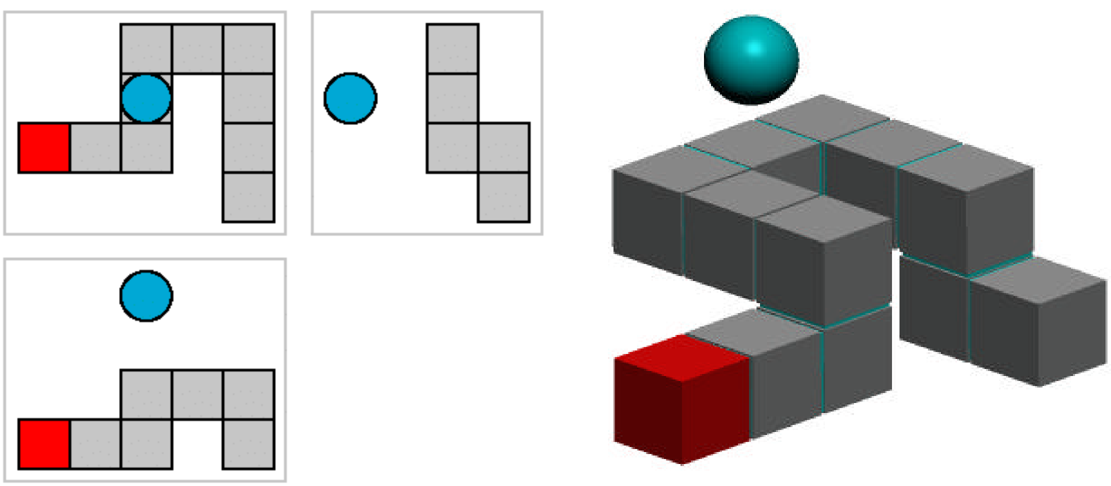

Figure 3. 2-D and 3-D views of an example block and ball used by St. John et al. (2001).

The block stimuli were chosen for their simplicity and generality to test the hypothesis while minimizing confounding variables. How might the results generalize to more complex and natural stimuli that are likely to be shown in C2 displays? To investigate this issue, we extended our hypothesis in three experiments involving complex terrain (St. John, Smallman, Oonk & Cowen, 2000; St. John, Oonk & Cowen, 2000). Participants viewed a 7 by 9 mile piece of terrain depicted in 2-D or 3-D with or without shading and grids on the ground-plane. Briefly, in one Terrain Experiment, participants chose the correct ground-level view from among four alternatives (see Figure 4). For this shape understanding task, participants were faster with the 3-D views. In another experiment, participants judged whether or not the position of one location was visible

from another location or obstructed by intervening terrain. These tasks both involved shape understanding because it hinged on understanding the gross layout of the terrain. Again, participants were faster with the 3-D views. In other Terrain Experiments, participants judged which of two locations was higher and how to get from one location to another. For these relative position tasks, participants were more accurate with the 2-D topographic maps, confirming our hypothesis.

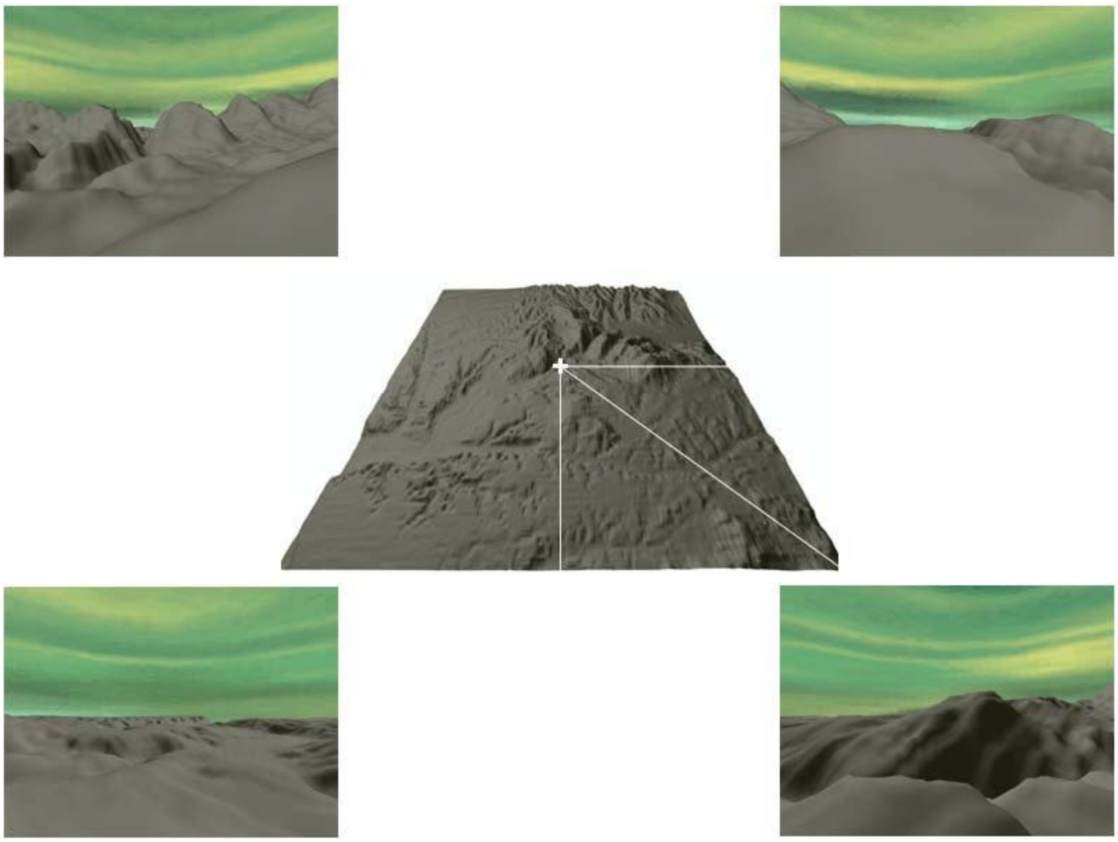

Figure 4. A trial in the Four-Corners task (St. John, Oonk & Cowen, 2000). Participants imagine standing on the ground at the white cross and looking to the southeast. They then pick the correct view from the four alternatives. The correct answer is top-right.

One obvious way of improving localization with 3-D displays is to increase the depth cues in them (Nagata, 1993). Static 3-D perspective displays may have as few as three of the 10 cues available to normal vision (occlusion, linear perspective and shading). Certain other cues (e.g. texture gradients and atmospheric haze) increase display realism (and hence desirability to users) but do not increase localization performance. For example, our own research has shown that varying the relative size of tracks is a poor way to improve users' ability to localize them in space in air warfare displays (Smallman, Schiller & Cowen, 2000). Further, consider that if all 10 depth cues were present, we would have achieved the perceptual performance of regular vision. That may not be

something to be proud of - a century of perceptual work since Helmholtz has documented the fallibility of, and inaccuracies inherent in human depth perception.

Recently, we have begun to address the question of whether the geometry of perspective projection makes 3-D perspective displays *inherently* poorer for relative position tasks (Smallman, St. John & Cowen, 2002). We hypothesized that the visual system can only generate precise relative position estimates from affine-transformed (roughly speaking, linearly transformed) image geometry. When faced with non-affine transformations (e.g. perspective projections), the system will resort to the use of the most linear cues available to reconstruct the scene and these may be suboptimal, hence deteriorating relative position performance. Consistent with this novel theory, we empirically measured and then mathematically modeled the perceptual biases found in participants' perceptual reconstruction of 3-D scenes. Participants reconstructed the length of 10 test posts scattered across a 3-D scene to match the physical length of a reference post. The test posts were all oriented in the X, Y or Z cardinal directions of 3-D space. Four viewing angles from 90 degrees ("2-D") down to 22.5 degrees ("3-D") were used. Participants' reconstructions of pole lengths systematically underestimated the compression of distances into the scene (Y) and systematically overestimated the compression of height (Z). The length mismatches could be modeled by assuming that linear perspective (that only operates accurately in X) is inappropriately used to scale matching lengths in all three dimensions of space. Only the 90 degree (2-D) view led to correct matches to both the X and Y dimensions. This theory actually offers a novel explanation of why perceived distances are systematically underestimated in the real world.

In sum, when "where" matters with some precision, use a 2-D view of a scene. However, when only a gross sense of the layout or shape of the scene is required, a 3-D view can be useful.

What

In addition to where a track is in space, there is the issue of **what** that track is – it's identity. The AADC display is popular partly because it depicts aircraft and ships as miniature realistic icons whereas conventional C2 displays show them as less familiar, military symbols (see Figure 5).

Using a battery of tasks including naming (Smallman, St. John, Oonk, & Cowen, 2000), recall (Smallman, Schiller, & Mitchell, 2000) and visual search (Smallman, Oonk, St. John, & Cowen, 2001) for standard military symbols (MIL-STD-2525B, US Department of Defense, 1996) compared with realistic icons, we have found a fairly consistent pattern of results. As we found in the Where section above, the beguiling realism of 3-D perspective view displays actually serves to undermine their utility for many tasks. An iconic code retains a visual similarity between the depicted object and its referent. When what has to be displayed is a set of inherently similar objects (many aircraft look somewhat alike, as do many ships) then users will have difficulty discriminating their icons and will consistently misidentify them (see Figure 5). Abstract symbols, on the

other hand, can be made arbitrarily distinct. However, we have found that icons are superior to symbols for conveying category (air or sea) and heading information.

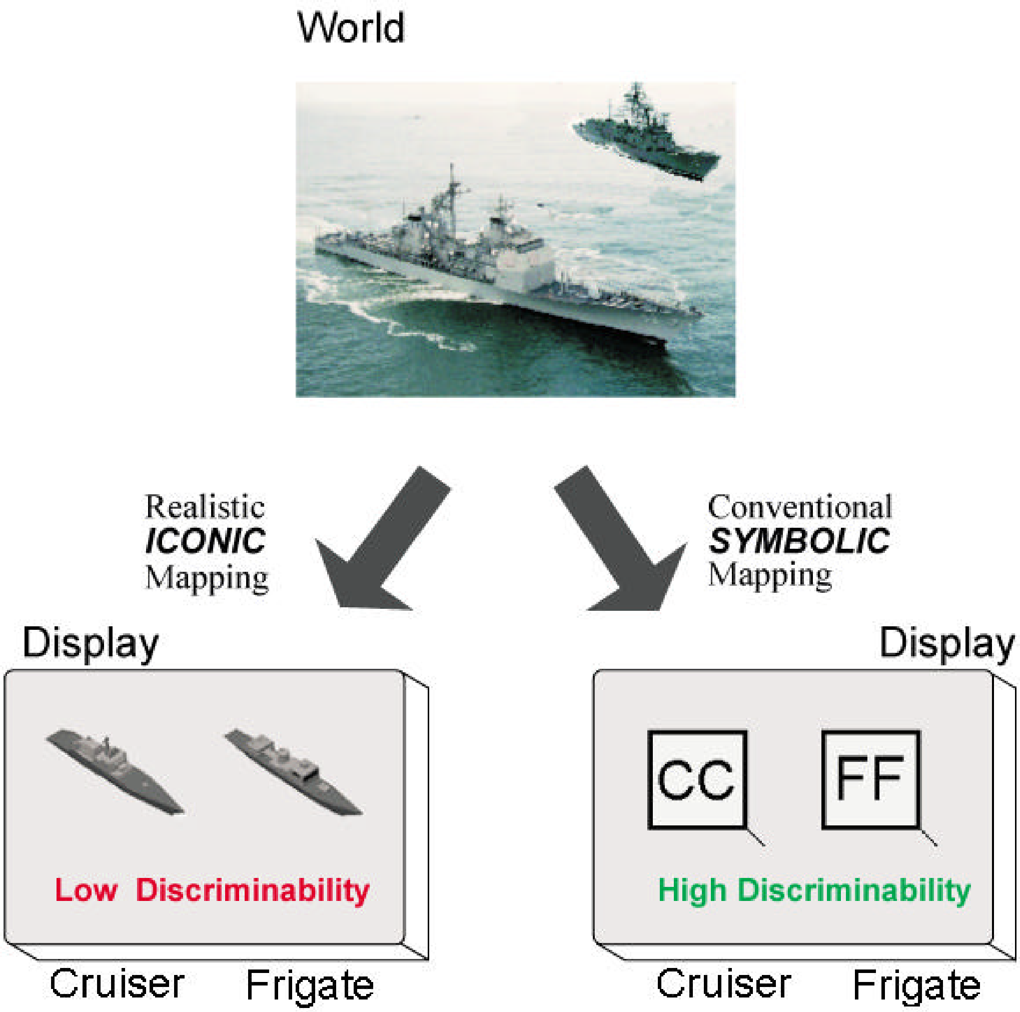

Figure 5. Two ways of mapping real-world military platforms onto a display, left, as realistic 3-D icons, right, as 2-D symbols - from the Military Standard 2525B symbol set (from Smallman, Oonk, St. John & Cowen, 2000).

The complimentary advantages of symbols for some attributes (platform identify and affiliation) and icons for others (heading and platform category) suggested to us the potential of a new symbology that combines the best aspects of symbols and icons. We call this hybrid symbology "Symbicons", see Figure 6.

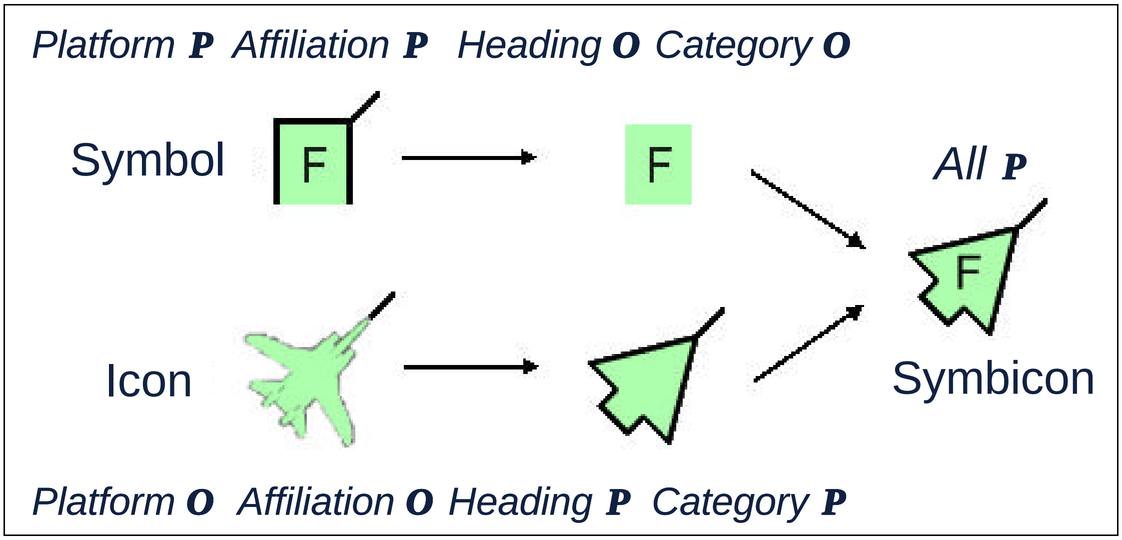

Figure 6. A fighter Symbicon is created by combining the interior of a conventional MIL-STD-2525B symbol with a discriminable, cartooned outline of a realistic icon. Symbicons are intended to combine the best aspects of symbols and icons (from Smallman, St. John, Oonk & Cowen, 2001).

In a visual search experiment, we established that Symbicons were as good, if not better, in either speed or errors, for all four of the asset attributes listed in Figure 6 (Smallman, St. John, Oonk & Cowen, 2001). Hence, Symbicons were shown to successfully combine the best aspects of symbols and icons.

In sum, when "what" matters, discriminable caricatures may be more effective than full realism, even if full realism is preferred by users.

How

C2 tasks are complex and are likely to contain task elements that require both shape understanding (better in 3-D) and also comprehending the relative position of objects (better in 2-D). **How** should displays, or suites of displays be used to best serve the complex task requirements of C2? To address this question empirically, we have developed a quasi-realistic C2 tactical routing task (the "Antenna task") that requires threading a chain of antennas across terrain while remaining out of line of sight of enemy units (St. John, Smallman, Bank & Cowen, 2001).

The Antenna Task is fairly difficult (see Figure 7). It requires placing a number of antennas in precise locations that satisfy a large number of constraints concerning the shape of the terrain and multiple lines of sight. The task requires a good understanding of the shape of the terrain for finding promising routes and for hiding antennas, which we previously found to be easier using a 3-D view. The Antenna Task also requires precise judgments of line of sight based on the relative heights and distances among antennas and the terrain. The relative benefits of 2-D and 3-D views for this aspect of the task is more

difficult to predict. In previous work (St. John et al., 2001), participants judged whether two points on terrain were in view of each other. This task appeared to require only a very gross understanding of the terrain – whether a large mountain or range of hills was obstructing a view, and in fact, a 3-D perspective view proved superior to a 2-D topographic view. In contrast, line of sight judgments in the antenna task often require far more precision to determine whether antennas are just in or out of a line of sight. This fine precision hinges on obtaining precise judgments of the distances, angles, and relative heights of points on the terrain. We previously found such tasks to be easier using a 2-D view. In contrast to finding generally promising routes, then, the exact placements of the antennas may benefit from a 2-D view.

We found that the Antenna task was difficult but performed better with the 2-D view than the 3-D view. We believe that this is so because participants were forced to spend the majority of their time involved in the fine placement of antennas on the maps which was a precise relative position task.

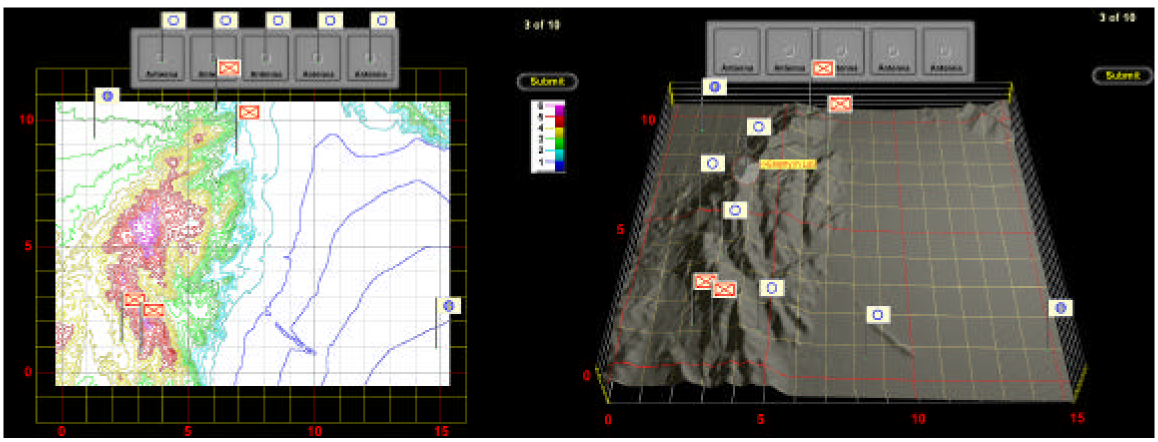

Figure 7. The 2-D plan view (left) and 3-D perspective view (right) in the antenna placement experiment. Enemy positions are identified by flags with a red "X". Antennas are identified by flags with blue circles (from St. John, Smallman, Bank & Cowen, 2001).

In a follow-on experiment, called "pick-a-path", participants were shown three potential routes across the terrain for constructing their chain of antennas (St. John, Smallman, Bank & Cowen, 2001). One of the three routes was much more promising than the other two, in that it followed canyons, and skirted hill tops to remain out of enemy lines of sight. Participants were shown the terrain and routes in either 2-D topographic views or 3-D perspective views. Performance using the 3-D perspective views was much faster. This result suggested to us a new human factors design concept for C2 that we call Orient and Operate. Users orient to the layout of a scene using a 3-D view, but then switch to 2-D views to interact with and operate on the scene. A 3-D view may work best to gain a basic grasp of the terrain, the shapes and locations of routes and objects. However, 3-D may be too ambiguous and distorted for precise judgments. Once a rough sense of layout and shape are obtained, a 2-D view may work best for achieving a precise grasp of relative positions and exact shapes.

Further supporting the Orient and Operate concept, we found that participants performed the best when provided both a 2-D plan view and a 3-D perspective view side by side. However, the effect was of small magnitude and we believe that better configurations of views are possible. Our suspicion is that placing views side by side, although a natural first step at display combination, is not an optimal arrangement for creating an effective suite of displays. Moving from one view to the other requires considerable re-orientation to the scene by the user. What are needed now are methods for improving the correspondences between objects in the views that will alleviate the effects of re-orientation. The concept of visual momentum (see Woods, 1984) offers ideas, such as the use of natural and artificial landmarks and consistent and compatible representations (Wickens and Carswell, 1995), for improving the correspondence between multiple views. Investigation of these and other concepts is currently underway.

Conclusions

3-D perspective view displays are coming. They are compelling and attractive to users because of their realism, but counter to many of our intuitions, they are actually less useful for a range of C2 tasks than well-designed 2-D displays. There is more to display design than photo-realism. Users are better served by designers who consider the nature of the user's tasks and then tailor the display view, symbology and depth cues to best suit those specific tasks. Finally, consider that without experimental research programs such as the one reviewed here, users might be given 3-D perspective displays for C2 tasks that are inappropriate and interfere with their job performance.

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